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APUL – Current Lead Design

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Abstract

The Accelerator Project for Upgrade of LHC (APUL) is a U.S. project participating in and contributing to CERN's Large Hadron Collider (LHC) upgrade program. In collaboration with Brookhaven National Laboratory, Fermilab's part of the upgrade includes several current lead design efforts.

A concept of main and auxiliary helium flow was developed that allows the superconductor to remain cold while the lead body warms up to prevent upper section frosting. The auxiliary flow will subsequently cool the thermal shields of the DFX Box and the transmission line cryostats. A thermal analysis of the current lead central heat exchange section was performed using analytic and FEA techniques.

A method of remote soldering was developed that allows the current leads to be field replaceable. The remote solder joint was designed to be made without flux or additional solder, and able to be remade up to ten full cycles.

A method of upper section attachment was developed that allows high pressure sealing of the helium volume with the ability to unbolt and remake the connection with a new seal. This design also provides the necessary electrical isolation of the current lead.

Test fixtures for both remote soldering and upper section attachment for the 13 kA lead were produced. The cooling concept, thermal analyses, and test results from both remote soldering and upper section attachment fixtures are presented.

Introduction

The current leads for the APUL Project are installed into vertical tubes contained in a large Distribution Feed Box (DFX). The DXF is located outside the tunnel containing the magnets being powered. The DXF box and Superconducting Link (SC Link) which carries current to the accelerator magnets are also part of Fermilab's responsibility [1], [2].

The most recent electrical scheme specifies current leads in four sizes: 13 kA x 4, 7 kA x 2, 2.5 kA x 8, and 0.6 kA x 8. All current leads are planned to be conventional copper (without a high

temperature superconducting section) operating at 300 K at the top down to 4.7 K at the bottom where current is transmitted into a superconducting cable.

The 13 kA lead is made from 101.6 mm diameter tellurium copper, UNS C14500, which provides the desired RRR value of ~ 20 [3]. The one-piece lead body (see Figure 2) contains an upper section, a central heat exchange section, and a lower end with the male part of the remote soldering connection.

The current lead is lowered into the DFX vertical tube and is remotely soldered into a separate copper piece which stays in the DFX. This separate piece, known as the receiver block, contains the female part of the remote soldering connection and connects at the bottom to a 13 kA cable from the SC Link. The lower heat exchange section keeps the SC link cable cold.

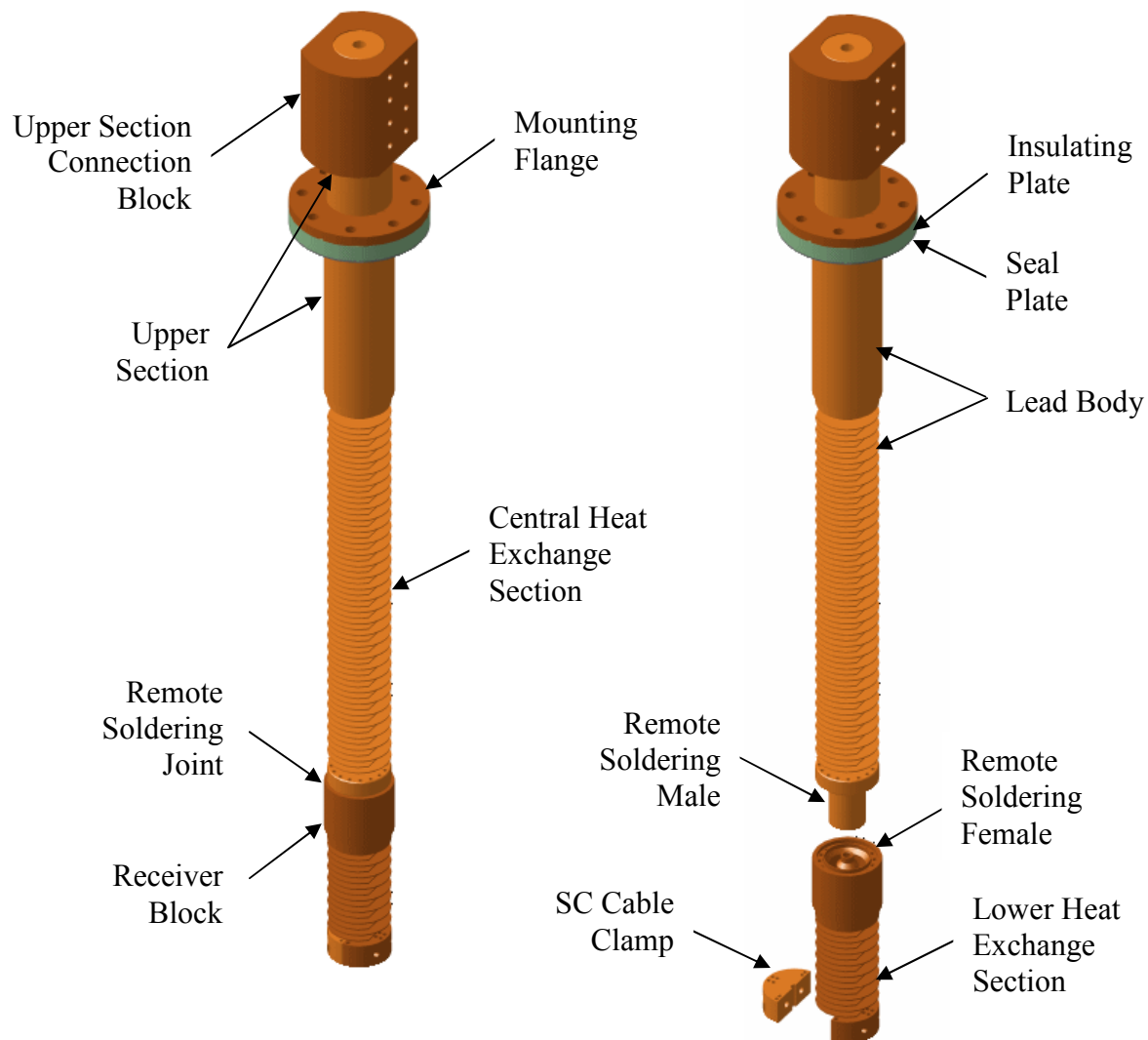


Figure 1 – 13 kA Current Lead and Receiver Block Models



Cooling Concept

In the APUL project cooling concept, the central pipe of the SC Link cryostat will carry the SC cables and supply 4.7 K, 3 bar supercritical helium to the base of each receiver block [4]. Helium will flow through the fins of the lower heat exchange section and through a series of holes surrounding the remote solder joint. At this point the helium flow will be split.

Some of the helium will flow into an auxiliary tube which will exit the current lead helium volume and cool the thermal shields surrounding the helium vessel in the DFX box. This auxiliary flow will also cool the SC Link cryostat thermal shields and return to be routed out of the DFX box and into the 300 K, 1 bar helium return line.

The main helium flow will pass through the fins of the central heat exchange section and be warmed up to near room temperature. At the upper end of the heat exchange section, this helium will flow into a centrally located insulated bayonet which also connects to the 300 K, 1 bar helium return line.

Valves will be used to control the helium flow through both the main and auxiliary flow paths, with the goal of controlling the temperature of the exposed current lead upper section to eliminate frosting.

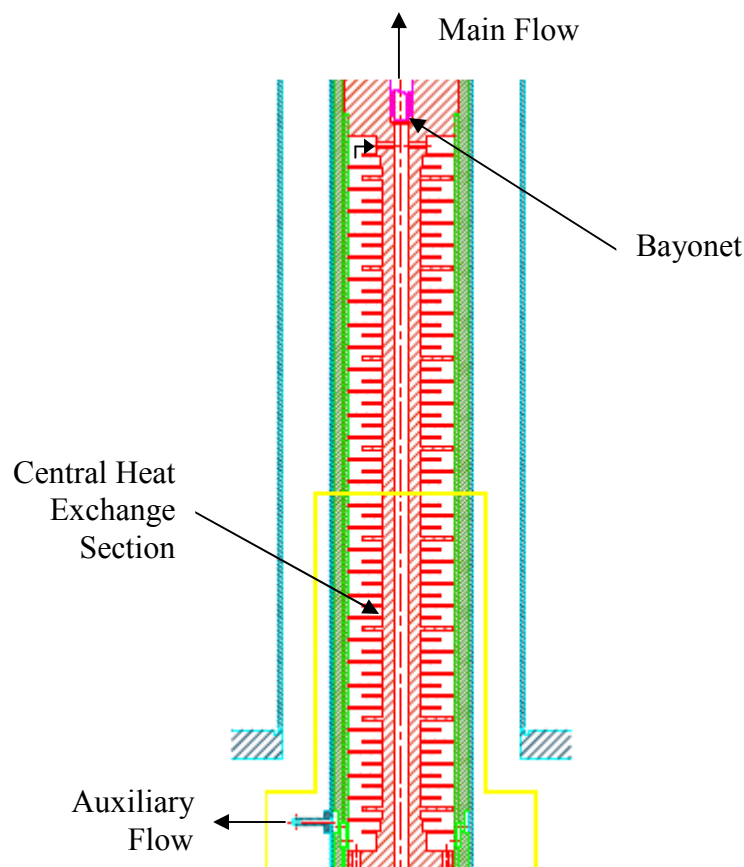


Figure 3 – 13 kA Central Heat Exchange Section Layout and Helium Flow

Heat Exchange Section

The central and lower heat exchange sections are taken from the CERN 13 kA current lead design shown on CERN drawing LHCDFLAS0030 [5]. The diameters of the section were scaled up to allow a 12.7 mm diameter cartridge heater to be inserted down the length of the lead for remote soldering.

A study of the heat exchange section parameters was performed and documented in a Fermilab Technical Note [3]. This document analyzed the materials chosen and calculated the section dimensions required to safely carry the current and optimize the section electrical and thermal performance.

A thermal analysis was then performed to verify that the design would perform as specified. This thermal analysis included both analytic and finite element analysis techniques. The modeling of the heat exchange section and helium flow paths was complex and the resulting computations were quite resource intensive. The work was documented in a Fermilab Technical Note [6].

This document concludes that the analytical calculation of convection coefficient is reasonably simple and accurate in determining the lead thermal performance, and verifies that the heat exchange section will function as desired in regards to helium flow and temperature requirements.

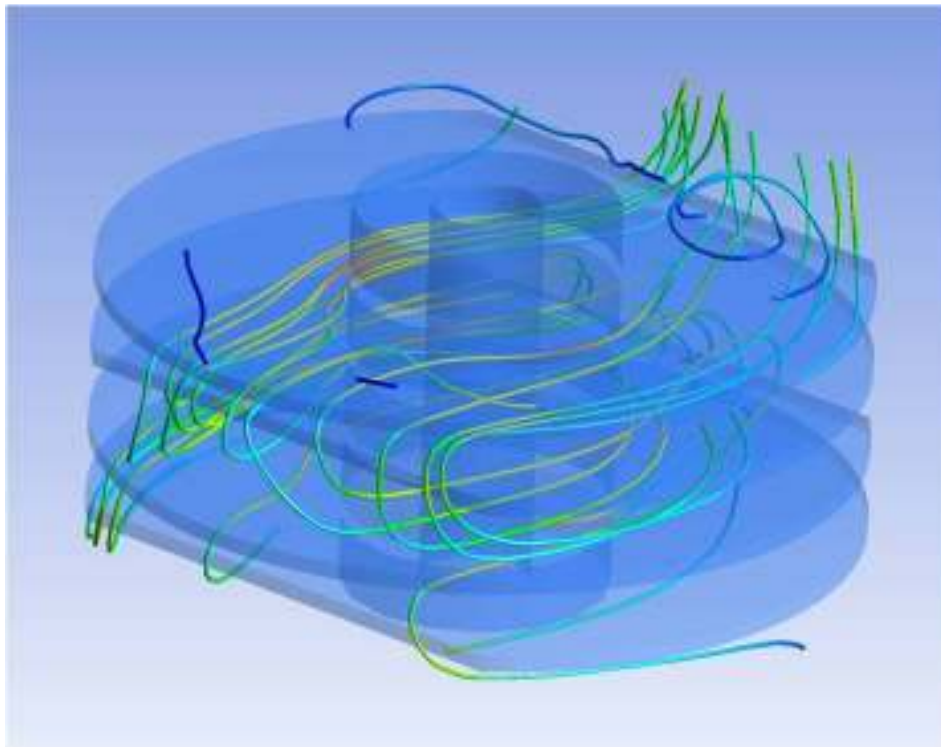


Figure 4 – FEA of Helium Flow Around Heat Exchange Fins

Remote Soldering Design

A method of remote soldering was developed that allows the current leads to be field replaceable without using flux or additional solder. This technique was first employed at Fermilab in an HTS current lead design with IGC Technology Development (now SuperPower, Inc.) in 1999. The remote soldering feature also allows the leads to be tested in a DFX box instead of a Dewar, ensuring lead performance under actual operating conditions.

The male part of the remote soldering joint (located at the end of the current lead body) is shaped like a 76.2 mm long tube with a nominal 54.0 mm OD and 31.8 mm ID, producing a nominal solder contact area of 186 cm². The female part of the joint (located at the top of the receiver block) is a machined annular connection slot of the same nominal dimensions but sized to provide a radial solder gap of 0.08 to 0.13 mm and a bottom solder gap of 0.08 to 0.46 mm.

Two annular overflow grooves are machined in the receiver block on either side of the connection slot. These overflow grooves collect excess solder above the joint. On separation, the tapered sides of these overflow grooves allow the solder to flow back into the bottom of the connection slot. The overflow grooves are sized to hold 1.4 times the solder volume used.

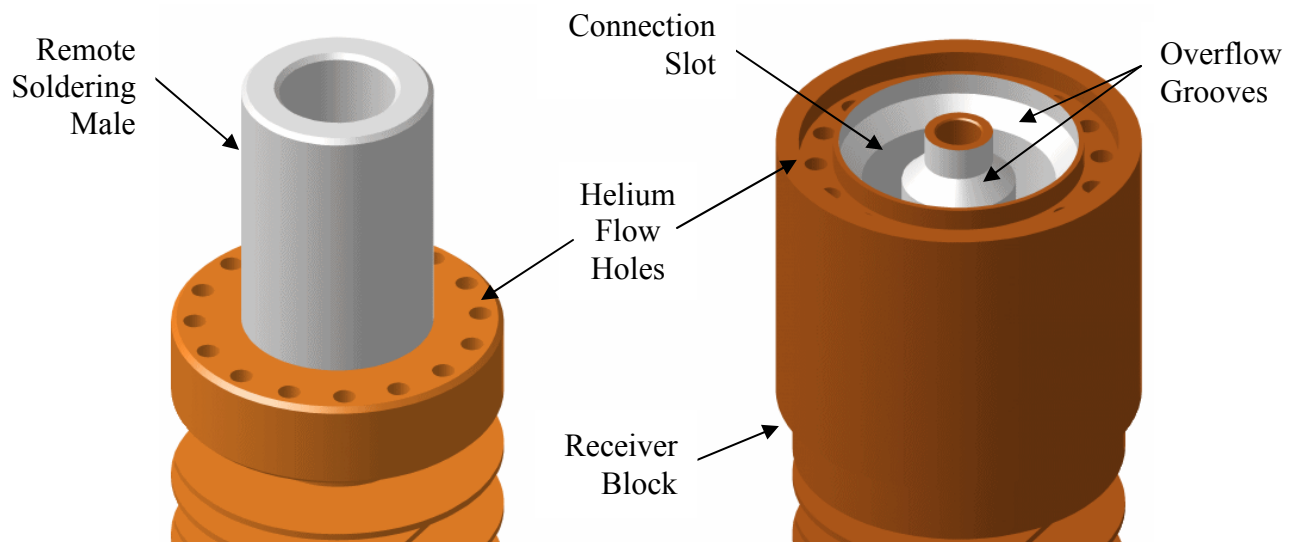


Figure 5 – Detail of Remote Soldering Ends (male end inverted for clarity)

The chosen solder and flux is Indium Corporation Indalloy #1E (a 52In/48Sn eutectic solder with a liquidus temperature of 118 °C) and #4-OA water soluble liquid flux. The flux is used *only* for the initial pre-tinning of the joint surfaces and every subsequent joint is made without flux or added solder.

Indalloy #1E was chosen because of a desire to make the subsequent joints without flux to avoid possible flux residue contamination of the helium system. This solder contains no lead (Pb), which satisfies European restrictions. Indium is also superconducting and malleable at our design temperature, and can form a superconducting contact joint even under zero wetting conditions.

Because indium and copper diffuse into one another creating brittle inter-metallic formations, the copper surfaces of the solder joint were nickel plated by electroless process per SAE specification AMS-C-26074, Class 1, Grade B, 0.0025 to 0.0127 mm thick as illustrated in Figure 5.

The chosen solder volume was 78 g, which would fill the overflow grooves 40% full under maximum engagement or allow a 3 mm gap at the bottom of the joint with no overflow. This allows a reasonable positioning tolerance on the receiver block in the DXF box and ensures that the lead never bottoms out in the receiver block before upper section seal contact.

Remote Soldering Test Fixture

A fixture was designed, built, and used to test the remote soldering design. The lead section and the receiver block were both machined from 101.6 mm diameter tellurium copper. All dimensions were according to the production design, except that no heat exchange fins were machined and a slot was cut in the lead section to allow the solder overflows to be viewed.

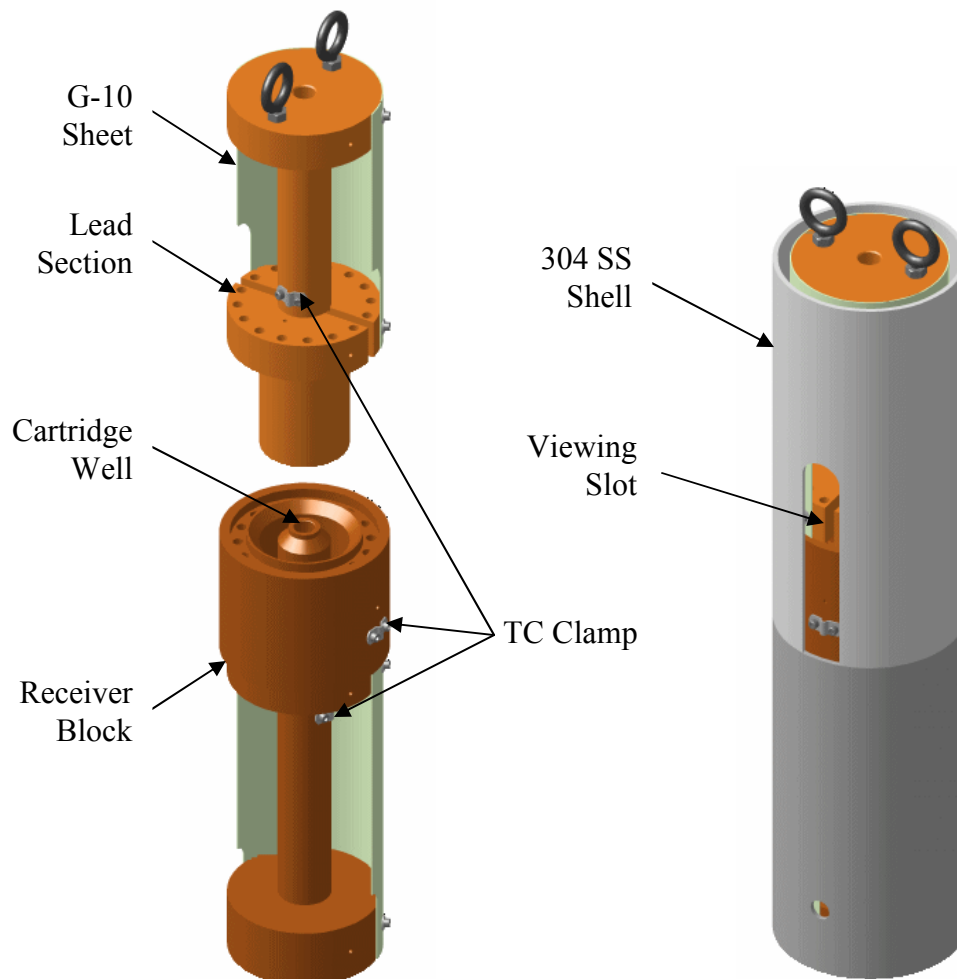


Figure 6 –Remote Soldering Test Fixture Models

An 800 watt SS cartridge heater, 12.7 mm diameter and 101.6 mm long (Watlow #J4A-15037) was specified. The heater was sprayed with a Boron-Nitride high temp release agent, ZYP Coatings #BN Aerosol, and allowed to cure overnight. The heater was inserted through the lead section and into the cartridge well of the receiver block.

The joint surfaces and solder wire were cleaned and degreased, and coated with liquid flux. The coil of solder wire was inserted into the connection slot of the receiver block. The lead section assembly was then lowered into the connection slot until it bottomed out on the solder wire.

A thermocouple is contained in the body of the cartridge heater and three additional thermocouples, Omega #5LSC-GG-K-20-72, were attached under the TC clamps. Four G-10 sheets were attached to simulate an insulating tube, and a 304 SS shell was installed to simulate the DFX vertical tube.

A custom 10 amp, 120 volt Watlow single control console containing a #PM6R1CA-AAAAAAA controller was used to power the heater. One of the four thermocouples was used to control heater powering and the other three were monitored.

The first heat cycle controlled off the thermocouple in the body of the receiver block. The controller was set for 165 °C on Indium Corporation advice. The fixture reached 118 °C in 10 min and the lead section lowered into the receiver block. The fixture reached the control temperature in 17 min.

The solder was observed to rise evenly in both the inner and outer overflow grooves. The heater power was ramped down, the heater withdrawn and the fixture separated, pre-tinning the solder surfaces. After cooling to room temperature, all surfaces were thoroughly cleaned of flux residue. Nineteen more heat cycles (ten full separate and join cycles) were performed, all using the original solder volume with no flux.

Several control methods were used, with the final full cycle controlling off the cartridge heater thermocouple. This control method requires no additional instrumentation attached to the lead or receiver block that would require a feedthrough to exit the DXF box. To simulate the first heat cycle, the controller was programmed to ramp from 0 to 330 °C in 30 seconds, soak at 330 °C for 16.5 min, ramp from 330 to 0 °C in 2 min, and then power off the heater.

Temperature readings were recorded at all thermocouples for every heat cycle. The lead section and receiver block were weighed after every separation to determine potential solder loss and solder volume distribution, measured for solder film thickness, and examined for solder film degradation. A test report was documented in a Fermilab Technical Note [7].

Upper Section Design

A method of upper section attachment was developed that allows the current leads to be field replaceable and facilitates the remote soldering design. There were several design goals.

The upper section connection block retains the bolt pattern found on the CERN 13 kA current lead design shown on CERN drawing LHCDFLAS0039 [5]. The block was made as shown in Figure 1 to allow access to the central hole in the lead body and to position the electrical power cable as close to the top plate as possible for thermal considerations.

The most recent functional specification for the APUL cold power transfer system has an 8 bar nominal design pressure [1], so the upper section attachment was designed for a 12 bar maximum pressure.

A single metal seal was desired, and a Garlock Helicoflex HNV200 Delta Seal, with a 139.93 mm seal OD, 3.30 mm diameter cross-section, alloy 600 Al jacket, and a 6,124 kg seating load was chosen. The seal sits in a groove in the DFX vertical tube top plate, and seals against a 304 SS seal plate bonded to underside of the current lead mounting flange.

The current lead must be electrically isolated from the DFX box and a system of G-10 insulating tubes and plates was designed to do this. The allowable leakage is less than 10 μ A at 2 kV potential. One of the insulating plates is bonded between the underside of the current lead mounting flange and the seal plate using 3-M Scotch-Weld 2216 translucent epoxy. All exposed G-10 surfaces are specified to be coated with grey Si-Coat 570 RTV silicone high voltage insulator coating.

Upper Section Test Fixture

A fixture was designed, built, and used to test the upper section design. The lead section body was fabricated from 101.6 mm diameter tellurium copper, and the flange from UNS C11000 copper plate. Because of the oxygen content of these alloys, e-beam welding and vacuum furnace brazing were excluded. The flange was joined to the lead body by torch brazing using Excel Silvaloy 15 brazing rod, and Harris Stay-Silv black Hi-Temp paste flux.

The brazement was grit-blasted and thoroughly cleaned and degreased. The insulating and seal plates were bonded to the flange, clamped together, and cured overnight at 66°C. All exposed G-10 surfaces and insulators were coated with Si-Coat 570 and allowed to cure at room temperature for 7 days.

The pressure can was made from 304 SS and was designed to simulate a DFX box vertical tube top plate. The components were welded together and a Swagelok SS-400-1-2 fitting was installed using Anti-Seize Sealant AST-Seal-PH #22545 on the NPT threads. A 60 cm length of 1/4 inch 304 SS tubing was installed in the fitting and the assembly leak checked.

The first metal seal was installed in the pressure can groove, the internal G-10 insulator tube inserted, and the lead section assembly lowered into place. Bolt insulators, upper insulating plate, and 304 SS clamp plate were positioned, and eight steel 3/8-16 UNC socket head cap screws x 101.6 mm long were installed with Belleville washers under the heads (McMaster-Carr part #91274A352 and #97125K41). A 194 kg-cm torque was applied to the bolts in two steps, using an alternating pattern and producing an 880 kg clamping force per bolt.

The fixture was pumped out and backfilled with 1 bar He gas. A high voltage standoff test was performed at 2 kV. The measured leakage was $0.02\ \mu\text{A}$. The fixture was assembled into a vacuum vessel which also serves as a pressure test containment vessel, and then pressure tested with 12 bar nitrogen gas for 10 min with no detectable pressure drop.

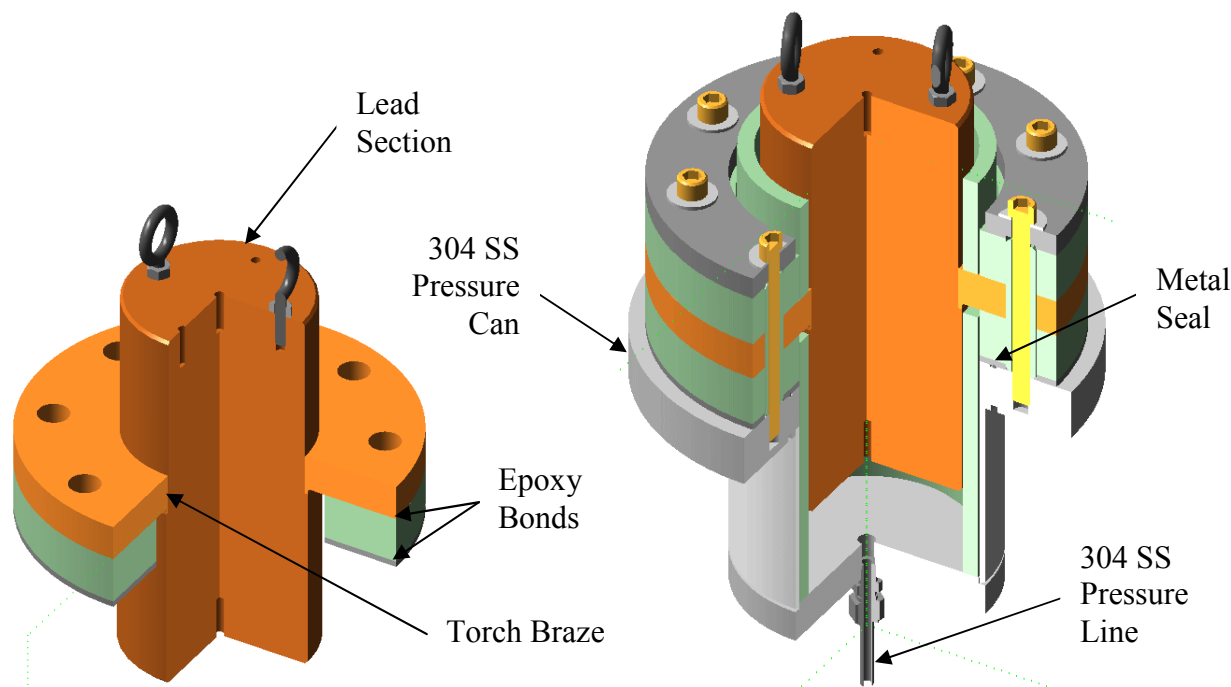


Figure 7 – Upper Section Test Fixture Models

The vacuum vessel was then pumped down, and the fixture pressurized with 3 bar helium gas and leak checked under actual operating conditions. No leak was detected on the most sensitive scale after 5 min.

The fixture was then removed from the vacuum vessel and cold-shocked in a liquid nitrogen bath. The liquid level was maintained at 32 mm to cool the exposed copper lead section. The fixture soaked for 25 min after the liquid level stabilized, and was removed from the nitrogen bath to warm up. Because of a need to repeat the cold-shock on that day, the fixture was submerged in hot water for 15 min. The cold-shock test was repeated and the fixture allowed to warm up overnight in air.

The fixture was reinstalled in the vacuum vessel and the leak check repeated. Again, no leak was detected on the most sensitive scale after 5 min. The fixture was removed from the vacuum vessel and the high voltage standoff test repeated. The measured leakage was $0.01\ \mu\text{A}$.

The fixture was disassembled, the first seal inspected, and a second new seal installed. This second seal underwent another pressure test and another leak check, passing both. A third new seal was installed. This third seal underwent another pressure test and another leak check, passing both. A test report was documented in a Fermilab Technical Note [8].

Conclusion

The tests and analyses performed demonstrate that the APUL current lead design satisfies all system operational requirements and specifications. The cooling concept and control methods are based on proven cryogenic principles and processes. Analytic and finite element analyses show the heat exchange section of the current leads will perform as required in regards to flow and temperature considerations.

The method of upper section attachment and sealing was proven to be reliable and repeatable. The tests simulated actual operating conditions. The metal seal, copper braze joint, and epoxy bonds retained 1.5 times the maximum design pressure and remained helium leak tight. The electrical isolation exceeded requirements even under extreme temperature and moisture conditions.

The method of remote soldering was proven to be effective and repeatable. The solder joint was separated and remade 10 full cycles with the original solder volume and without flux. No flux residue will be present to potentially contaminate the helium, no solder will need to be added deep inside the DFX box, and no additional instrumentation will be required.

The chosen solder functioned well and the solder film remained consistent throughout all heat cycles. The cartridge heater, control system, and control method were all proven to be sufficient and effective. The tests proved that the APUL current leads will meet all project requirements and can be reliably replaced *in situ* without DXF box disturbance.

References

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